SUPPLEMENTARY INFORMATION

1 Determination of lattice angles and spacing

To characterize our imaging system and to determine the lattice structure, we used a fluorescence image of a dilute thermal could, similar to the inset in Fig. 1 of the main text. The lattice axes are oriented at approximately $\pm 45^\circ$ with respect to our images. A precise determination of this angle and the lattice spacing is needed so that the deconvolution algorithm works with high fidelity. We first determined the center positions of isolated atoms from this image by a simple fitting algorithm. The histogram of the mutual distances projected in a coordinate system rotated by an angle θ clearly shows the periodicity of the lattice (see Fig. 1a,b) and the visibility of the pattern depends very sensitively on θ. For a quantitative analysis, we fit a sum of equidistant Gaussians to the histogram. The width of the Gaussians for different values of θ (Fig. 1c) shows a clear minimum at $\theta = 45.85(1)^\circ$. We obtained a similar graph for the other lattice axis and found an angle of $-45.55(1)^\circ$. The distance of the Gaussians is $4.269(4)$ pixel which corresponds to lattice period of $532\,\mathrm{nm}$. Thus, our magnification factor is 128.4(2) and one pixel of the CCD camera corresponds to 124.6(1) nm in the object plane. The angles and lattice spacing determined by this method are used as fixed parameters for our deconvolution algorithm. We also found that the phases of the two lattice axes slightly drift from shot to shot. They are determined for each image by fitting the center positions of single atoms in the outer part of the images.

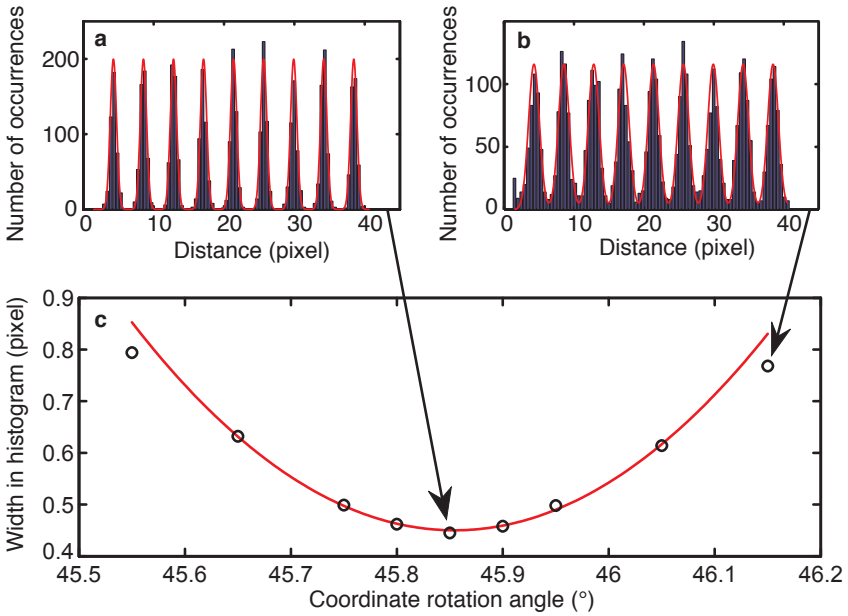

Figure 1 **Determination of the lattice angles.** **a,b** Histogram of the distances between the center positions of individual atoms projected in a coordinate system rotated by an angle θ. The line is a fit to a sum of equidistant Gaussians. **c** The width of the fitted Gaussians show a clear minimum. The red line is a parabolic fit and yields a minimum rotation angle at $\theta = 45.85(1)^\circ$.

2 Determination of the point spread function

We determined our point spread function (PSF) from the fluorescence image of a dilute atomic cloud. We summed the fluorescence image of many individual atoms that were isolated from their neighbors by more that 12 pixels. The summed image is almost radially symmetric and we computed an azimuthal average (see Fig. 2). We expect our PSF to be a convolution of an Airy disk with a Gaussian, taking into account fluctuations of the lattice with respect to the imaging system and the width of the atomic wavepacket in the potential wells. Due to this convolution, the first minimum of the airy pattern is not visible in our averaged signal. We found that our PSF can be well approximated by a double Gaussian:

$$PSF(x,y) = C\left[(1-a)\exp\left(-0.5(x^2+y^2)/\sigma_1^2\right) + a\exp\left(-0.5(x^2+y^2)/\sigma_2^2\right)\right] \qquad (1)$$

with widths σ_1, σ_2 and a parameter a describing the relative amplitudes. The maximum fluorescence level C varies from day to day and is in the range of 800-1200 counts.

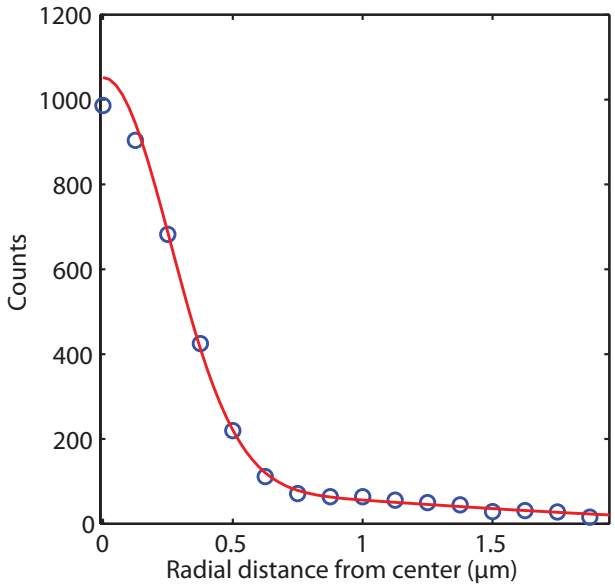

Figure 2 Azimuthal average of our experimentally obtained point spread function. The data was obtained by averaging over 68 signals of single atoms. The line is a fit with the double Gaussian of Eq. (1) and yields $\sigma_1 = 2.06(5)$ pixels, $\sigma_2 = 9.6(1.2)$ pixels, $a = 0.075(2)$ and $C = 1050(7)$.

3 Single-band Hubbard parameters

For a z-lattice depth of $V_z = 26E_r$, the single-band Hubbard parameters for our 2D system are given in the following table:

$V_{x,y}(E_r)$	J/h (Hz)	U/h (Hz)
5	134	382
10	39	607
15	13	776
20	5	917
25	2	1039

Note that one expects the the single-band Hubbard parameters to be slightly renormalized due to multi-orbital effects.